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Rejuvenating Organic Soil Behavior with Crushed Waste Concrete: Experimental and Mineralogical Investigations

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Abstract

Urban regions are currently grappling with the mounting challenge of managing substantial volumes of solid waste, especially from building and demolition materials. This study explores the utilization of Crushed Waste Concrete (CWC), a substantial component of solid waste, for organic soil stabilization. Various percentages (10%, 15%, and 20%) of crushed waste concrete were added to organic soil. Subsequently, a comprehensive series of laboratory tests were conducted, including compaction tests using the standard Proctor test, Unconfined Compressive Strength (UCS) tests, and Physicochemical assessments comprising of pH, Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray (EDX), and X-ray diffraction (XRD) analyses. The results of the experimental tests revealed interesting outcomes. As the percentage of crushed concrete increased, there were corresponding increases and decreases in the organic soil's maximum dry density and optimum water content, respectively. Notably, the UCS values of the organic soil exhibited an enhancement of approximately 594% when the CWC percentage was 10%. The SEM-EDX and XRD analyses provided valuable insights, indicating an improvement in the soil structure and the presence of new cementitious materials such as calcium-aluminate-hydrate (CAH) and calcium-silicate-hydrate (CSH) resulting from the interaction between crushed waste concrete and organic soil. This study demonstrates the potential of crushed waste concrete as an effective agent for organic soil stabilization, offering a sustainable approach for repurposing solid waste and mitigating soil-related challenges in urban regions. The findings suggest promising prospects for further exploration and application of this eco-friendly technique in civil engineering and construction practices, contributing to waste reduction and environmental preservation.

1. Introduction

The aim of soil stabilization encompasses enhancing shear resistance, reducing permeability, and achieving greater firmness for coarse-grained soils, while achieving consistency for fine-grained soil conditions. Techniques such as compaction, preloading, drainage, soil mixing, and chemical stabilization present potential avenues for reinforcing soil. Effective selection of stabilizers must align with the specific soil types for optimal results. In a broader context, soil treatment and stabilization encompass various methodologies aimed at enhancing soil mechanics and curbing construction expenses [1]. Using additives such as lime, Portland cement, or their combinations has been prevalent among engineers practicing geotechnical solutions to bolster soil stability and mechanical properties across diverse soil compositions. Within geotechnical practices, the incorporation of waste materials has gained significant popularity. By repurposing waste, this approach mitigates environmental waste accumulation and reduces storage costs. It also offers an economically viable alternative to costly additives or even enables a reduction in its application[2].

The surging demand for new developments has contributed to a notable upswing in waste generation [3], [4]. Construction activities generate substantial volumes of concrete waste during building or demolition processes, constituting a substantial fraction (30-40%) of the total waste stream [5]. Similarly, concrete and material laboratories amass substantial quantities of concrete specimens for testing purposes, leading to mounting concerns over environmental implications arising from waste accumulation in such contexts [6]. The escalating waste production has direct implications on the prevalence of illegal dumping, with Malaysia experiencing pronounced challenges in this regard [7]. Considering these circumstances, proactive measures are essential to curb waste accumulation and develop effective strategies to combat waste, pollution, resource depletion, and environmental degradation, ensuring the sustainable preservation of our ecosystem.

Biddle the utilization of concrete waste as an amendment for weak soils introduces a transformative impact through hydration reactions, engendering an increase in soil pH, Ca^{2+} content, and free Ca(OH)2. These constituents engage in pozzolanic reactions, facilitating an enhancement in soil quality. The consequential hydration and pozzolanic reactions harness the water present within the soil, instigating a fortification that renders the soil more robust, simultaneously diminishing its susceptibility to volumetric fluctuations such as swelling and shrinking. As a result, the overall engineering performance of the soil experiences a marked improvement in life [8].

The realm of geotechnical engineering grapples with the challenge of peat soils, renowned for their elevated compressibility, abundant water content, and compromised shear strength [9]. Organic soil presence gives rise to an assortment of challenges for engineering projects, materializing as construction conundrums, post-construction setbacks, increased expenses, maintenance requirements, and long-lasting ramifications. Characterized by organic contents often surpassing the 50% threshold, these soils require extensive approaches for stabilizing and reinforcing them to improve their strength and mitigate changes in volume. These measures serve a dual objective: preventing potential damage to superstructures and reducing the need for extensive maintenance or replacement.

Significantly, several studies have been conducted to enhance the stability of inorganic soils, such as clay and sand, through the utilization of concrete waste. One study focused on evaluating both the geotechnical and environmental attributes of construction and demolition waste materials when used in the pavement subbase. The results indicated that recycled concrete aggregate outperformed conventional granular materials in terms of geotechnical properties and demonstrated environmental sustainability [10]. Additionally, Jain and Chawda [11] put effort into incorporating well-graded crushed concrete waste (at varying percentages of 0.5%, 10%, and 25%) into clayey soil. Consequently, significant enhancements in the soil's geotechnical characteristics, yield satisfactory outcomes.

In a separate investigation, waste concrete fines were utilized to assess their impact on the California Bearing Ratio (CBR) value of soil. The study involved varying the proportion of waste concrete fines from 10% to 40%. Remarkably, the CBR value of the soil exhibited significant enhancements following the introduction of waste concrete fines [12]. Similarly, cohesive soils with an initial undrained shear strength of 6.78 kPa experienced improvements when treated with crushed concrete in a ground state (sieve #4) at proportions of 5%, 10%, and 15%. These treatments lead to an impressive increase in unconfined compressive strength, accompanied by a notable reduction in compressibility [13].

Furthermore, an experimental investigation evaluated the possibility of utilizing recycled concrete aggregates to enhance clay soils' shear and compressive strengths and deformation properties. The test results indicated that the incorporation of recycled concrete aggregates into clay soils resulted in lower dry density and higher unconfined compressive strength (UCS), which further improved with extended moist curing [14]. In another study, different proportions (ranging from 10% to 40%) of Concrete Grinding Residue (CGR) were mixed with two soil types classified as A-4 and A-6 according to AASHTO standards. The strength tests indicated that soils stabilized with CGR exhibited increased strength properties. Furthermore, laboratory tests demonstrated that concrete grinding residue treatment reduced the maximum dry unit weight and plasticity while increasing the soil's pH [15]. Lastly, an experimental study investigated the utilization of recycled concrete aggregates to improve the strength properties of clay soil, reinforced with recycled tire polymer fibers and glass fibers. The findings emphasized that higher recycled concrete aggregate content and longer curing times significantly improved both the unconfined compressive and tensile strengths compared to clay soil alone [16].

However, a notable research gap emerges in the context of utilizing CW to enhance the stability of organic soils. More precisely, there has been limited exploration of CW in the stabilization of organic and peat soil. This knowledge gap prompted investigations such as that conducted by Ibrahim et al. [17], who examined the viability of employing DCW for peat stabilization across various proportions (ranging from 10% to 50%). A comprehensive series of tests were conducted, the findings are significant, since they indicate improvements in UCS and Maximum Dry Density (MDD), as well as a decrease in swell potential.

In this context, this study presents and discusses the influence of CWC fractions on the mechanical behavior of organic soil. This is based on the outcomes of a series of unconfined compression tests conducted on organic soil samples with different CWC ratios. The primary objective of this study is to evaluate the potential of using CWC in the stabilization of organic soil.

Consequently, the principal contributions of this study are as follows:

i) Investigate the suitable admixtures for enhancing the strength of organic soil utilizing CWC, construction and demolition waste generated from institutional waste.

ii) Determine the properties of unconfined compressive strength and compaction parameters for organic soil stabilized with CWC.

iii) Determine the mineralogical compositions of both unstabilized organic soil and stabilized organic soil using X-ray diffraction (XRD).

iv) Examine the morphological and elemental characteristics of unstabilized organic soil and stabilized organic soil using a scanning electron microscope (SEM) equipped with an energy-dispersive x-ray tube (EDX).

2. Material Specifications

2.1 Organic Soil

The naturally occurring organic soil collected from Gebeng, Pahang, Malaysia, was chosen for the experimental investigation. Fig. 1 shows the mean soil gradation, and Table 1 presents the basic soil properties. The mineralogical content of organic soil exerts an influence on its geotechnical properties and behavior. Therefore, the mineralogical composition of the organic soil investigated in this study was assessed using semi-quantitative X-ray diffraction (XRD) analysis, and the results are presented in Table 2. The quantification of minerals, as provided in Table 2, shows that the main elements are C (41.8%), O (35.8%) Al_2O_3 (7.38%), and SiO_2 (10.4%), accompanied by CaO, Fe_2O_3, MgO, and SO_3.

Table 1 *Basic soil-engineering properties of organic soil*

Properties	Method	Value/ measure
Moisture Content (%)	BS 1377 Part 2: 1990	138
Organic Content (%)	ASTM D 2974-87	57.6
Specific Gravity	BS 1377: Part 2: 1990	1.7
Liquid Limit (%)	BS1377-2: 1990	113
Plastic Limit (%)	BS1377-2: 1990	88.8
Plasticity Index	BS 1377-4: 1990	24.0
Maximum Dry Density (g/cm^3)	BS 1377-4: 1990	0.69
Optimum Moisture Content (%)	BS 1377-4: 1990	60.78
pH	BS 1377-1990	3.6
UCS (kPa)	BS1377-7: 1975	36

2.2 Crushed Waste Concrete (CWC)

The crushed waste concrete (CWC) was acquired from the Concrete and Material Laboratory in Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Gambang, Pahang, Malaysia. The substantial dimensions of CWC fragments make it unsuitable for direct utilization in experimental geotechnical studies due to the limited capacity of laboratory equipment, which typically operates at small to medium scales. Consequently, the large fragments were reduced into smaller CWC particles via a two-step process. Following the requirements specified in ASTM

C535, the shards were initially broken down with a sledgehammer, followed by abrasion and impact in the Los Angeles machine. The study incorporated a final CWC gradation with a maximum particle size of 2 mm (No. 10 standard ASTM sieve) as shown in Fig. 1.

The specific gravity of CWC was determined to be 2.60, as per the (ASTM D854). This observation is consistent with previous research indicating that CWC particles have a significant degree of porosity and micro-cracking. Fig. 2 shows (SEM) images of the CWC materials. As observed, coarse agglomerated fragments. The chemical composition of the CWC, determined by XRD analysis (Table 2) indicates that the primary chemical components of CWC are CaO (30.4%) and SiO_2 (39.8%). The presence of CaO and SiO_2 in both primary constituents, namely natural aggregates and cement mortar, of CWC is a predictable observation. In general, the X-ray diffraction (XRD) results are consistent with prior research on the chemical components of CWC [18], [14], [16].

During the testing program, the required quantity of CWC was allocated based on the CWC fractions that passed through ASTM standard aperture sizes. This approach ensures consistency among the CWC particles used in the experimental work.

Table 2 *Mineralogical composition of organic soil and CWC*

Elements/ Minerals	Mass (%)	
	Organic soil	CWC
C	41.8	18.1
O	35.8	47
Ca	0.08	17.3
Si	4.67	15
Al2O3	7.38	-
SiO2	10.4	39.8
CaO	0.125	30.4
Fe2O3	2.87	1.3
MgO	0.107	-
SO3	0.436	-

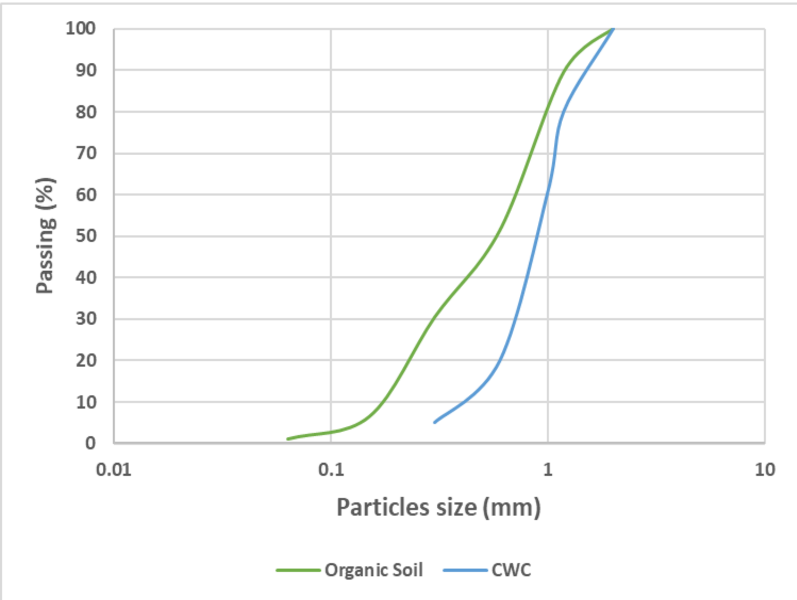

Fig. 1 *Gradations of organic soil and CWC*

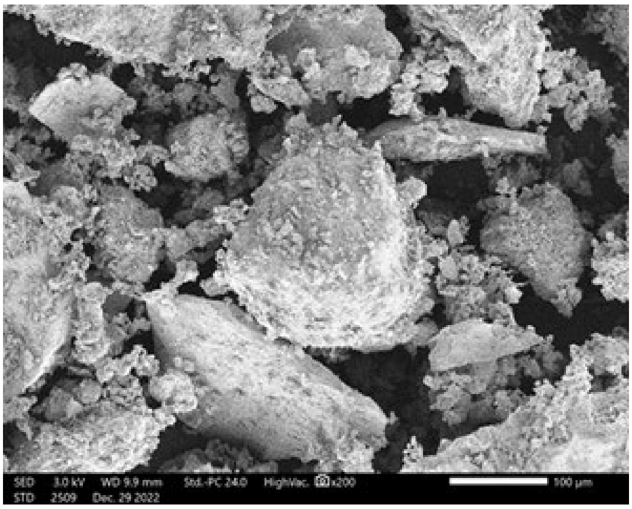

Fig. 2 *SEM images of the CWC*

3. Testing Methodology

The use of CWC to enhance the performance of organic soil was evaluated based on the mechanical, mineralogy, and microstructural properties of organic soil-CWC mixtures.

3.1 Organic Soil-CWC Mixtures

The organic soil-CWC mixtures were prepared through a dry blending process using fractions of CWC and soil. blending proportions were determined based on the following rule:

$$\%CWC = \frac{M_{CWC}}{M_{CWC} + M_{Soil}} \times 100 \quad (1)$$

Here, %CWC represents the percentage of CWC in the mixture, while M_{CWC} and M_{Soil} stand for the dry mass of CWC and organic soil, respectively. Three different %CWC levels (10%, 15%, and 20%) were selected for the experimental mixtures. The presence of a lower additive concentration, specifically below 5%, has an impact on the morphological and engineering characteristics of soil, but does not have a substantial influence on strength parameters [19]. For the organic soil-CWC blends, the initial step involved dry mixing of CWC and soil. Subsequently, distilled water (moisture) was gradually incorporated into the mixture while being carefully hand mixed to prevent clumping or balling, ensuring a uniform distribution of CWC throughout the blend. Further homogenization was achieved using a mechanical mixer before the mixture was compacted into test specimens.

3.2 Compaction Test

The compaction characteristics of the organic soil and organic soil-CWC mixtures were assessed through the determination of moisture-density relationship, maximum dry density (MDD), and optimum moisture content (OMC), following the guidelines outlined in (BS 1377: Part 4: 1990). To evaluate the compaction specifications of organic soil-CWC mixtures, the standard Proctor compaction procedure, as referenced in Tabatabaie et al. [16] and Kianimehr et al. [14] and other was employed. In practical engineering applications, it is customary to evaluate the strength needs of stabilized soils that have undergone standard compaction [20]. For the composite soil with CWC, compaction was performed after the addition of water because the interactions between CWC and soil may influence compaction characteristics [14], [16].

3.3 Unconfined Compressive Strength Test

The Unconfined Compressive Strength (UCS) is well recognized as a prominent indicator for evaluating the effectiveness of soil stabilization methods. The utilization of unconfined compressive testing has been widely regarded as a straightforward, reliable, and uncomplicated experimental method in numerous research investigations focused on construction and demolition waste [21]–[22] and [15]. For organic soil, and organic soil-CWC mixtures, unconfined compression tests were conducted following the guidelines of (BS1377: part 7: 1990).

Test specimens with a diameter of 38 mm and height of 76 mm were prepared in a layered pattern using a specifically designed vertical mold. After compaction, the specimens were extracted, and the dimensions of the cylindrical specimens were measured. Each test specimen corresponding to a certain organic soil-CWC was compacted to the compaction ratio at MDD and OMC. The loading device produced a displacement-controlled loading rate of 1 mm/min which was in the approved range (0.5 to 2%/min) [23].

For the organic soil-CWC, it is hypothesized that the curing process would trigger cementitious reactions, leading to a subsequent enhancement in UCS [24]. In this study the air-curing method was used; therefore, the cylindrical specimens utilized in the UCS test were wrapped in plastic wrap and placed in an airtight container during the curing process in a room environment. This was done to simulate the inherent conditions of the soil and consider potential enhancements in strength resulting from curing and moisture loss for periods of 7 and 28 days. After curing the samples were weighed before testing. The mean ultimate compressive stresses was used as the concluding value. To ensure the reliability of the findings, the UCS was assessed for three individual specimens of each specified blend [23].

Hence, to comply with established standards, a specimen diameter of 38 mm was determined in line with the British Standard (BS) requirement that the size of the largest soil particle should not exceed one-fifth of the specimen diameter. This guideline ensures accuracy in UCS testing. The maximum particle size (2 mm) comfortably adheres to this specification and maintains reliability of the UCS results.

3.4 X-ray Diffraction

X-ray diffraction (XRD) was performed to determine the mineralogical composition of organic soil. The soil sample with particles smaller than 75 µm, was placed onto the X-ray diffractometer for analysis (Rigaku TTRAX, Seifert XRD 3003 T=T).

3.5 Scanning Electron Microscope

Scanning Electron Microscopy (SEM) was conducted to investigate the morphologies and structures of organic soil samples using an (FEI Quanta 450 SEM instrument). Additionally, Energy-Dispersive X-ray Spectroscopy (EDX) was utilized to quantify the elemental composition of the samples. For the SEM-EDX analysis, both dry stabilized and unstabilized samples were coated with gold before being analyzed. The detailed morphological examination was conducted using SEM, which provided high-magnification imaging capability.

4. Results and Discussion

4.1 Compaction

Compaction curves depicting the characteristics of both the organic soil and organic soil-CWC mixtures are illustrated in Fig. 3. As shown, the inclusion of CWC content exerts a discernible influence on the compaction properties of organic soil, resulting in an elevation of the MDD and a corresponding reduction in the OMC. Comparatively, the stabilized organic soil exhibits an elevated MDD compared to its unstabilized counterpart. This enhancement can be primarily attributed to the establishment of interparticle bonds, which is a direct consequence of the pozzolanic activity facilitated by Ordinary Portland cement [25]. This pozzolanic reaction significantly mitigates the presence of inter-particle voids, culminating in denser material. Consequently, the stabilized organic soil necessitates a relatively diminished water requirement to attain maximum density—a direct outcome of the pozzolanic reaction—compared to unstabilized organic soil. Similar compaction behavior was also demonstrated in [11], [17].

The pronounced effect of CWC on compaction properties can be predominantly ascribed to the augmentation of the organic soil's density during the stabilization process, facilitated by the displacement of certain soil moisture through the introduction of the stabilizing agent.

An increase in dry density indicates a corresponding reduction in the void ratio, resulting in a compact soil structure. This variance in the MDD could be attributed to fluctuations in the voids ratio induced by the inclusion of CWC [26]. For the specific purpose of soil stabilization, the augmentation of MDD and the reduction in OMC of the soil are highly desirable traits for stabilizing agents. In this context, CWC can be judiciously introduced into the soil at an appropriate rate, thereby minimizing potential negative impacts on compaction characteristics of the original soil. This strategic approach ensures that the benefits of stabilization are harnessed while preserving the favorable compaction attributes of soil [27].

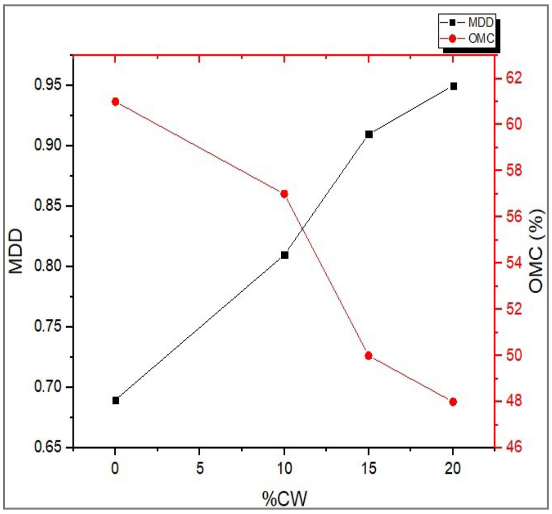

Fig. 3 *Compaction test for organic soil and organic soil-CWC*

4.2 pH

Table 3 presents the pH values of organic soil, CWC, and organic soil supplemented with 10% CWC. The addition of CWC to organic soil exerted an alkalizing effect, increasing soil pH. The pH analysis was conducted to validate CWC's capacity to neutralize the pH of organic soil. The observed elevation in the pH of the peat soil from 3.5 to 7.3 provides tangible evidence that CWC elevated the pH of the soil mixture through the liberation of hydroxide ions (OH^-) and calcium ions (Ca^{2+}) into the soil. These released ions effectively counteract acidic compounds, serving as neutralizing agents. Furthermore, the interaction between the additives and the acidic constituents of low-pH soil could engender the formation of novel compounds and alter the soil's mineral composition, thereby enhancing its strength and microstructural characteristics. This elevated pH level enhanced cation exchange dynamics within the soil matrix, fostering flocculation and aggregation processes and cementitious compound formation [15], [28]–[29].

Table 3 *pH values of organic soil, CWC, and organic soil-CWC mixtures*

Type of sample	pH value
Organic soil	3.60
CWC	11.70
Organic soil with 10% CWC (7 days of curing)	4.70
Organic soil with 10% CW (28 days of curing)	7.30

4.3 Unconfined Compressive Strength

Each sample was subjected to UCS testing to evaluate its shear strength. The UCS test identified the optimal mix design for organic soil stabilization using CWC. The control sample exhibited low strength at 36 kPa. The strength of the uncured organic soil-CWC specimens is shown in Fig. 4. A noticeable trend was observed as the addition of CWC into the soil increased UCS.

In addition, an obvious increase in UCS was observed in specimens subjected to air curing. This trend is exemplified in Fig. 5, where the mixture with a CWC content of 10% exhibits a progressive increase in UCS with prolonged curing. At 28-days of curing, the UCS reached 180 kPa, a marked enhancement compared to the uncured specimen (UCS = 82 kPa) and the unstabilized organic soil (UCS = 36 kPa).

The UCS findings highlight the interaction between curing length and CWC, which influences the strength characteristics of organic soil-CWC mixtures. A comparative analysis suggests that curing duration exerts a more substantial influence than the percentage of CWC in enhancing UCS. Prolonged curing consistently led to significant UCS increases, a phenomenon that was particularly pronounced in specimens subjected to air curing. Two noteworthy conclusions can be drawn: firstly, specimens with extended curing periods and identical %CWC values exhibited higher UCS; secondly, at the same curing duration, a specimen with 10% RCA content exhibited superior UCS.

The enhanced soil strength arises from short-term (cation exchange and dissociation) and long-term (pozzolanic) reactions. Pozzolanic reactions generate C-S-H, C-A-H gels, and ettringite structures, characterized by fiber-like structures and cementing properties that bolster cohesion among soil particles. Several processes, including cation exchange reactions, flocculation, agglomeration, and long-term pozzolanic reactions, play a dominant role in controlling the physiochemical phenomena associated with the stabilization of expansive soils. Ca^{+2} ions from (CaO) content in CWC, together with silica and alumina in the soil, undergo chemical reactions, including cation exchange, dissociation, pozzolanic processes, and cementitious processes [14], [19], [30]–[31].

Evident from the substantial UCS surge after 28 days of curing, strong chemical bonding between CWC and organic soil particles emerged, particularly in mixtures containing 10% CWC. Meanwhile, the short-term increase in shear strength observed in organic soil-CWC mixtures can be attributed to the mechanical influence of CWC.

The UCS results underscore the positive influence of both curing duration and CWC content on the compressive strength of organic soil-CWC mixtures. This underscores the potential of CWC as a stabilizing agent, with an optimal strength improvement achieved through 10% content and extended curing. Fig. 6 shows an exemplar photograph of an organic soil-CWC mixture subjected to UCS testing.

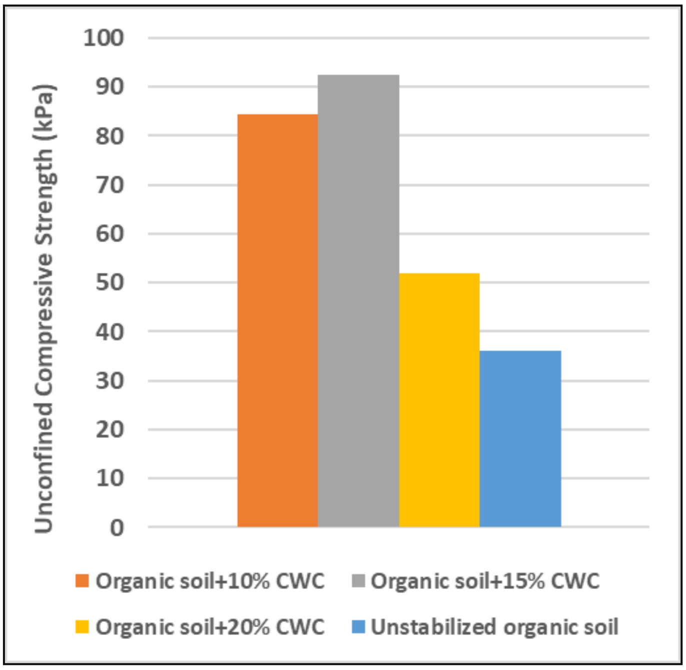

Fig. 4 *Unconfined compressive strength of unstabilized organic soil and uncured organic soil-CWC mixtures*

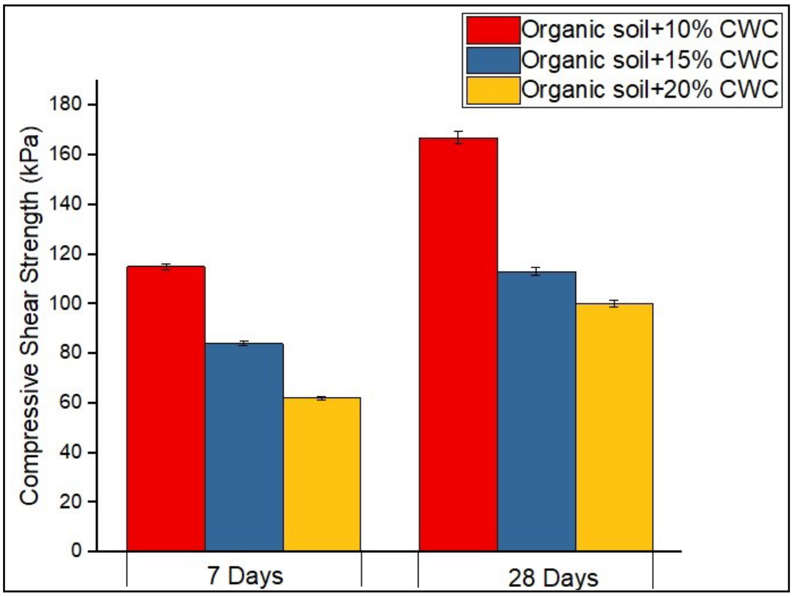

Fig. 5 *Unconfined compressive strength of organic soil and cured organic soil-CWC mixtures*

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Fig. 6 *Unconfined compression test of the organic soil-CWC composite*

4.4 XRD

A detailed XRD analysis was conducted on the organic soil with 10% CWC after a curing period of 28 days. XRD analysis of the specimens was conducted to investigate the cementitious products based on their crystallographic nature. To understand the mineralogical changes in the soil stabilized with CWC, XRD images of unstabilized organic soil and organic soil with 10% CWC after curing for 28 days are given in Fig. 7. The identification of different phases in the figures was carried out using X-ray diffraction (XRD) analysis. The XRD analysis was performed in the range of 5 to 80 2-theta values using an X-ray polycrystal diffractometer. The scan speed employed throughout the analysis was 0.6 2θ min^{-1}. It was observed that after 28 days of curing, distinct peaks associated with cementitious gels, namely C-S-H, C-A-H, and CASH developed. The occurrence of this phenomenon can be ascribed to the pozzolanic processes. The obtained results exhibit a high level of concordance with previous research findings.

Furthermore, the XRD analysis revealed additional cementitious compounds such as ettringite. This formation is a result of the dissolution of alumina and silica in the organic soil-CWC system. The presence of these cementitious compounds during longer curing periods is crucial for achieving a significant increase in the strength of the organic soil-CWC mixture. This validates the contribution of these compounds to the considerable strength improvement observed in the organic soil-CWC mixture after extended curing periods [14], [19], [32].

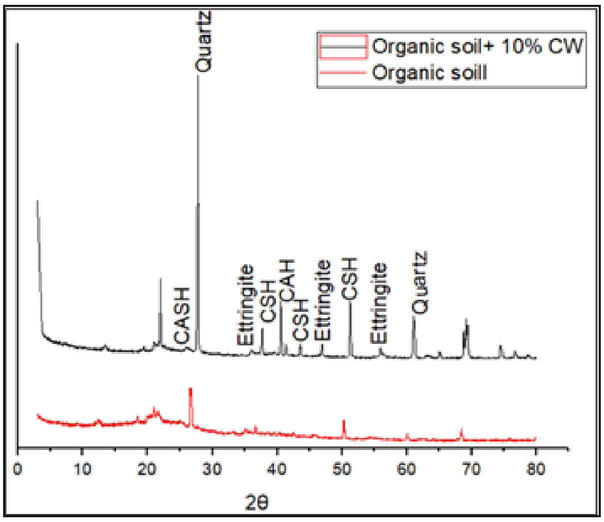


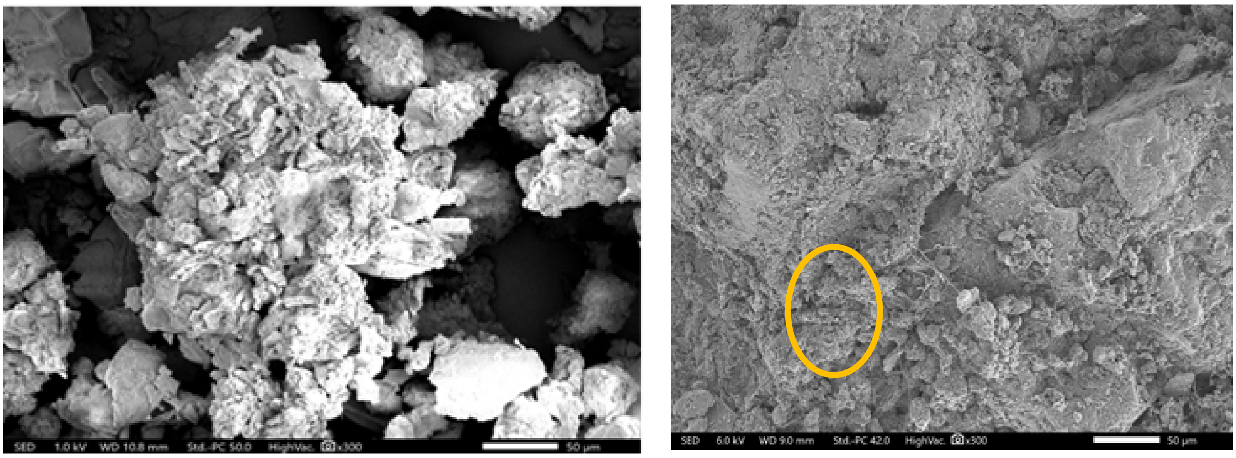
Fig. 7 *XRD analysis of unstabilized organic soil and organic soil with 10% CWC after 28 days of curing*

4.5 SEM-EDX

SEM and EDX analyses were performed on organic soil, CWC alone, and organic soil with 10% CWC mixture to investigate the microstructures of the materials and assess the alterations on the surface of soil particles resulting from the addition of CWC.

Fig. 8 shows the SEM morphologies of unstabilized organic soil and organic soil with 10% CWC specimens cured for 28 days. The SEM image of unstabilized soil (Fig. 8(a)) revealed a high occurrence of sheet-like particles, which can be due to the presence of organic fibers. Furthermore, the unstabilized soil exhibited a significant presence of inter-particle pores, which played a role in its structural vulnerability. These pores were characterized by bigger voids and equidimensional flakes that resembled thin films. In comparison with unstabilized soil, the organic soil-10% CWC exhibited a highly compacted soil structure (Fig. 8(b)). The SEM analysis shows that the cementitious substance of organic soil with 10% CWC in this study mainly consists of a reticular gel structure. The results of EDX analysis of the reticular gels occurring in the organic soil with 10% CWC specimen cured for 28 days are shown in Table 4. The presence of calcium (Ca), silicon (Si), and aluminum (Al) in the reticular gels provides conclusive evidence that the reaction product of the organic soil-10% CWC consists of CAH, CSH, and CASH gel. This result is in accordance with the above XRD analysis results and the observation reported by Almsedeen et al. [33] and Li et al. [34]. In addition, according to the data in Table 4, it can be seen that with the prolongation of curing time, the content of Al, Si, and Ca at 28 days significantly increases compared with that at 7 days. In addition, based on the data shown in Table 4, the concentrations of Al, Si, and Ca exhibited a notable increase after 28 days of curing in comparison to the concentrations observed after 7 days. Moreover, the elevated flocculation observed in Fig. 8(b) can be attributed to the rise in Ca^{+2} ions in the organic soil with a 10% content of (CWC) [19].

In addition, the needle-like products indicate the presence of ettringite. Essential conditions for ettringite formation are the presence of water, calcium, aluminum, and aluminum sulfate. Ettringite is produced through the reaction of calcium oxide (CaO) and activated alumina oxide (Al_2O_3), resulting in the formation of calcium aluminate hydrate (C-A-H). The intermediate compound further reacts with calcium sulfate dihydrate to produce ettringite. The ettringite generated within the stabilized soil plays a crucial role in enhancing soil bonding, consequently improving overall soil strength [35]. Consequently, a significant increase in strength was observed when using organic soil supplemented with 10% CWC, a finding supported by the results of the UCS test.



(a) (b)

Fig. 8 *SEM images of (a) Unstabilized organic soil; and (b) Organic soil with 10% CWC for 28 days of curing*

Table 4 *EDX analysis of organic soil and organic soil with 10% CWC over 7- and 28-days curing periods*

Soil	Curing period, Days	A (%)	Si (%)	Ca (%)	Al:Si
Organic Soil	-	1.19	1.12	0.03	1.06
Organic soil+10%CWC	7	8.5	9.9	1.4	0.49
	28	9.1	11.3	3.4	0.59

5. Conclusion

Recycling and reuse concrete waste materials play a vital role in safeguarding natural resources and minimizing environmental impact. This study conducted a comprehensive experimental assessment of the use of CWC for soil stabilization, specifically aimed at enhancing the strength and compaction properties of organic soils. Key findings of this study are as follows:

i) Incorporating CWC into organic soils reduces the content OMC and an increase in the MDD.

ii) The addition of CWC to organic soil enhances the UCS of the organic soil-CWC mixtures. Extended curing periods further enhance this strength, resulting in more durable compositions. In this study, the optimal CWC percentage was 10%. The UCS of unstabilized organic soil increased from 36 kPa to 180 kPa upon the addition of 10% CWC during a 28-day curing period.

iii) SEM-EDX and XRD analyses provide compelling evidence of the positive interaction between CWC and organic soil, resulting in improved soil structure characterized by increased compactness and minimized voids, along with the creation of new cementitious materials such as CSH, CAH and ettringite.

The central implication, however, is profound: stabilized soil exhibits substantial strength suitable for construction and building applications. This revelation holds particular significance for civil engineers, highlighting the potential of CWC—especially in greater quantities than tested herein—as a viable alternative to cement for organic soil stabilization. Although the economic viability of integrating CWC as a cement substitute may vary, its indisputable benefits include reduced landfill utilization and diminished carbon emissions.

As urban areas grapple with ongoing waste management challenges, this study provides a gateway to further exploration and widespread adoption of this innovative approach, fostering a more sustainable and resilient built environment. Future research delving into the intricate composition of soils, CWC chemistry, and the physio-chemical bonding between CWC and organic soil particles hold the promise of illuminating the behavior of organic soil-CWC mixtures in greater detail. These insights are expected to contribute significantly to the advancement of knowledge in this field.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: study conception and design: ***Ayah Almsedeen****: Writing the main manuscript, data collection, analysis, interpretation of results;* ***Mohd Fakhrurrazi****: Supervision, funding acquisition;* ***Nurmunira Muhammad****: Data validation, reviewing and editing the draft manuscript;* ***Sumi Siddiqua****: reviewing the manuscript;* ***Muhammad Nizam Zakaria****: Reviewing and approving the final version of the manuscript.*

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